

**PHASE CONTINUOUS SYNTHESIZER WITH PHASE COASTING AND
ASSOCIATED METHODS**

Field of the Invention

[0001] The present invention relates to the field of communication systems, and is particularly directed to a digitally controlled phase continuous synthesizer for relatively high frequency chirp applications, such as synthetic aperture radar (SAR) and the like, in which the synthesizer includes continuous phase calibration.

Background of the Invention

[0002] Synthetic aperture radar (SAR) systems, typically located on board an aircraft or satellite platform, provide SAR imagery of the radar return signals in both the range dimension and the cross-range or azimuth dimension. Range resolution is achieved in a well known manner by using either a high bandwidth fixed frequency transmit pulse or a frequency modulated (FM) transmit pulse. Resolution in the cross-range dimension is achieved by synthesizing a large antenna aperture using the motion of the radar platform. The key to SAR is the data processing of reflected return data. For an

overview of SAR, reference is made to "An Introduction To Synthetic Aperture Radar" by W. M. Brown and L. J. Porcello, IEEE Spectrum (September, 1969), pages 52-62.

[0003] For optimal performance, the frequency content of relatively high frequency communication signal processing systems, such as those used for generating wideband chirps for SAR, should be as pure as possible, in particular, they should exhibit phase continuity or coherency through the entire output frequency range. Analog synthesizer-based systems, which offer a relatively wide tuning range, suffer from arbitrary phase steps when switching between local oscillators. A direct digital synthesizer (DDS), on the other hand, provides phase continuity with low noise when switching, but is capable of operation within a relatively narrow tuning range (e.g., 100 MHz).

[0004] One technique currently used to generate a wideband chirp involves multiplying up the output chirp of a DDS to realize the desired output frequency range of the system. Unfortunately, successive multiplications also multiply noise by the same factor. This problem is compounded because radiation requirements typically limit the choice of DDS to those having relatively low frequency rates, which means that even higher multiplication factors are required. Another conventional approach is to limit the frequency range (width) of the chirp and use receiver processing to resolve phase errors associated with the discontinuities.

[0005] One conventional approach is disclosed in U.S. Patent No. 5,878,335 to Kushner which is directed to a low-power digital frequency synthesizer that combines direct digital frequency synthesis techniques with

serrodyne frequency translation principles to produce a wideband frequency response with high spectral purity. A DDS is used to generate a high-resolution analog carrier signal from a low-speed digital clock signal. The carrier signal is phase modulated by a low-resolution signal generated from a high-speed digital clock signal. The modulation signal is a higher frequency signal than the carrier signal, and the phase modulation is accomplished by exact decoded gain elements.

Summary of the Invention

[0006] In view of the foregoing background, it is therefore an object of the present invention to provide a phase continuous synthesizer and method in which the synthesizer includes phase coasting to reduce and/or eliminate undesired phase discontinuities in the output wideband swept frequency signal.

[0007] This and other objects, features, and advantages in accordance with the present invention are provided by an apparatus for generating a relatively wideband swept frequency signal including a first generator for generating a first swept frequency signal, and a second generator successively switching between different frequency signals while creating undesired phase discontinuities during switching. A mixer is connected to the first and second generators for mixing the first swept frequency signal and the successively switched different frequency signals to produce the relatively wideband swept frequency signal, and a phase coasting unit is connected downstream of the mixer to reduce the undesired phase discontinuities created during switching in the relatively wideband swept frequency signal.

[0008] The phase coasting unit is preferably a third-order phase locked loop (PLL) including a phase detector, a switch connected to the phase detector and controlled to open during a switching interval, a plurality of integrators downstream from the switch, and a voltage controlled oscillator downstream from the plurality of integrators. The second generator generates an offset frequency signal and successively combines the offset frequency signal with a reference frequency signal to produce the successively switched different frequency signals. The first generator comprises a first digital synthesizer to generate the first swept frequency signal.

[0009] The second generator may include a second digital synthesizer to generate the offset frequency signal, a plurality of frequency converters to successively combine the offset frequency signal with a reference frequency signal to produce the successively switched different frequency signals, and a controller for controlling the operation of the second digital synthesizer to maintain phase continuity between the successively switched different frequency signals.

[0010] Objects, features, and advantages in accordance with the present invention are also provided by a method for generating a relatively wideband swept frequency signal including generating a first swept frequency signal with a first generator, and successively switching between different frequency signals with a second generator while creating undesired phase discontinuities during switching. The first swept frequency signal is combined with the successively switched different frequency signals to produce the relatively wideband swept frequency signal, and the undesired phase discontinuities are reduced by coasting

over the undesired phase discontinuities in the relatively wideband swept frequency signal.

[0011] Again, this coasting is provided by a phase coasting unit, preferably a third-order phase locked loop (PLL), including a phase detector, a switch connected to the phase detector and controlled to open during a switching interval, a plurality of integrators downstream from the switch, and a voltage controlled oscillator downstream from the plurality of integrators.

[0012] Successively switching between different frequency signals preferably includes generating an offset frequency signal and successively combining the offset frequency signal with a reference frequency signal to produce the respective different frequency signals. Successively switching between different frequency signals may include connecting a plurality of frequency converters to an output of a reference frequency signal generator and coupling an offset frequency signal to the plurality of frequency converters to successively combine the offset frequency signal with the reference frequency signal to produce the different frequency signals. The first generator may be a first digital synthesizer, and the second generator may be a second digital synthesizer generating the offset frequency signal.

Brief Description of the Drawings

[0013] FIG. 1 is schematic block diagram of a phase continuous self-calibrating synthesizer according to the present invention.

[0014] FIG. 2 is a timing diagram of the phase continuous swept frequency signal output from the synthesizer of FIG. 1.

[0015] FIGs. 3A and 3B are enlarged views of a portion of the timing diagram of FIG. 2 illustrating detail of the phase continuous swept frequency signal at a switching point.

[0016] FIG. 4 is schematic block diagram of a phase continuous synthesizer including phase coasting according to another embodiment of the present invention.

[0017] FIG. 5 is a more detailed schematic block diagram of the phase coasting unit of the phase continuous synthesizer of FIG. 4.

Detailed Description of the Preferred Embodiments

[0018] The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout, and prime notation is used to indicate similar elements in alternative embodiments.

[0019] Before describing in detail the phase-continuous frequency synthesizer of the present invention, it should be noted that the invention resides primarily in a modular arrangement of communication circuits and components and an associated controller therefor, that controls the

operations of such circuits and components. In a practical implementation that facilitates their being packaged in a hardware-efficient equipment configuration, this modular arrangement may be implemented via an application specific integrated circuit (ASIC) chip set, for example.

[0020] Consequently, the architecture of the arrangement of circuits and components has been illustrated in the drawings by a readily understandable block diagram, which shows only those specific details that are pertinent to the present invention, so as not to obscure the disclosure with details which will be readily apparent to those skilled in the art having the benefit of the description herein. Thus, the block diagram illustration is primarily intended to show the major components of the invention in a convenient functional grouping, so that the present invention may be more readily understood.

[0021] Referring initially to FIG. 1, an embodiment of the phase-continuous frequency synthesizer of the present invention will now be described. The phase-continuous frequency synthesizer is diagrammatically illustrated as comprising a controlled 'fine' tune direct digital synthesizer (DDS) **10** that is operative, under the control of a controller **100**, to produce a linearly swept or ramp frequency output. By 'fine' tune is meant that DDS **10** has the finest spectral granularity of various frequency tuning components of the system. As a non-limiting example, the frequency ramp produced by DDS **10** may be swept over a range from 100 to 200 MHz. Thus, in this example, the 'finest' tuning range within the system is 100 MHz.

[0022] The DDS **10** is coupled to a prescribed reference frequency (e.g., 100 MHz) produced by a phase locked oscillator (PLO) **20**, which is coupled to receive a

frequency reference from an external source (not shown). This reference frequency is used to synchronize the various components of the synthesizer, and may be provided to the PLO 20 via a power divider 46.

[0023] The fine tune DDS 10 is coupled to a mixer 30. Frequency translation oscillator 50 is operative to produce a relatively high radio frequency (RF) output, e.g., an RF frequency on the order of 1.0 GHz. The output of mixer 30 is coupled to a first band pass filter 40 which is then coupled to a frequency mixer 70, which is also coupled to the output of a switch (S1) 80. Switch 80 is operative under processor control, via controller 100, to switch among a plurality of coarse frequency inputs (four in the illustrated example at 81, 82, 83 and 84), that are used to define a coarse range of operation of the synthesizer (the fine tuning range of which is established by DDS 10, as described above).

[0024] For this purpose, the respective inputs 81, 82, 83 and 84 of switch 80 are coupled to PLO 20 and to a set of cascaded frequency offset converters 110, 120 and 130. Each frequency offset converter produces an output frequency that is equal to the sum of its input frequencies and under the phase control of the offset frequency DDS 140. PLO 20 generates a base coarse frequency F_0 , while the frequency offset converters 110, 120 and 130 produce respective coarse frequencies F_1 , F_2 and F_3 , that are combinations of the base frequency F_0 and an a coarse offset frequency F_{off} generated by an offset DDS 140. Offset DDS 140 is operative under the control of the controller 100 to produce the coarse offset frequency F_{off} equal to the sweep range of fine tune DDS 10, which, in the present example, may be 50 MHz, as described above.

[0025] The output frequency F1 produced by frequency offset converter **110** is equal to the sum of the offset frequency Foff supplied by DDS **140** and the base frequency F0 supplied by PLO **20**; the output frequency F2 produced by offset converter **120** is equal to the sum of the offset frequency Foff and the frequency F1 supplied by offset converter **110**; and the output frequency F3 produced by offset converter **130** is equal to the sum of the offset frequency Foff and the frequency F2 supplied by offset converter **120**. Under the control of controller **100**, the phase of the offset frequency Foff produced by offset DDS **140** is controllably adjustable, so as to provide for phase-continuity at the instances of switching among the respective input frequencies to switch **80**. In particular, controller **100** sets the phase of the offset frequency Foff produced by offset DDS **140** to be equal to the negative of the measured phase error (discussed below), so that at the instant of switching between any of its inputs the new frequency to which switch **80** switches will be at zero degrees and phase continuous with the frequency from which switch **80** has switched. Of course, more than one switch **80** may be provided in combination with an associated multiplier and mixer to increase the sweep range of the chirp, as would be appreciated by the skilled artisan.

[0026] Mixer **70** provides the output chirp or swept frequency signal to another band pass filter **42** and a power divider **44**. The chirp is then typically provided to an up converter, transmitter and antenna as would be appreciated by the skilled artisan. However, undesired phase discontinuities in the chirp would normally occur during switching as will be described below.

[0027] Operation of the frequency synthesizer of Figure 1 will now be described. For purposes of the present example, the offset frequency F_{off} is 50 MHz, as referenced above. Initially, at time t_0 the phase of the offset frequency F_{off} produced by offset DDS **140** is controllably pre-set at zero phase. Also, switch **80** is coupled to receive the frequency F_0 from PLO **20**. As pointed out above, controller **100** sets the phase of the offset frequency F_{off} produced by offset DDS **140** to be equal to the negative value of overall phase error, so that at the instant of switching between any of their inputs the new frequencies to which switches **80** transition will be at zero degrees and phase continuous with the previous frequency. (It is to be understood that by "phase" is meant the relative difference between the pre-switched frequency and the post-switched frequency at the instant of switching, i.e., zero degrees difference and phase continuous.)

[0028] Whenever a transition is made to a new coarse frequency, the fine tune DDS **10** is reset to the beginning of its sweep and thereupon proceeds to ramp over its sweep range (100 MHz in the present example). Upon DDS **10** reaching the upper end of its sweep range, switch **80** switches to the next offset frequency F_1 following F_0 and the sweep of DDS **10** is restarted. The switch **80** sequentially transitions through its coarse frequency inputs **81** - **82** - **83** - **84**. Therefore, referring to the timing diagram of FIG. 2, at time t_0 , the output of the synthesizer is equal to the product of the frequency output F_x of the mixer **30** plus the lowest coarse frequency F_0 . Between time t_0 and time t_1 , as the frequency output of the fine tune DDS **10** ramps over its 100 Mhz range, the output of the synthesizer is linearly swept from $F_x + F_0$ to $F_x +$

$F_0 + F_{off}$ which equals $F_x + F_1$. Upon reaching the frequency $F_x + F_0 + F_{off}$ at time t_1 , fine tune DDS **10** returns to the base translation frequency F_x . However, since switch **80** is switched from input **81** to input **82**, the output of the synthesizer begins sweeping from $F_x + F_1$ to $F_x + F_1 + F_{off}$, and so on as the switch **80** is stepped through its additional inputs **83** and **84**.

[0029] Referring to FIG. 3A, the enlarged portion **3** of the timing diagram of FIG. 2 will be described. As discussed above, during the switching transients, e.g. at time t_1 , undesired phase discontinuities **A** would normally be created. Because phase continuity at the switching transients is needed to reduce SAR image degradation, such a synthesizer would typically require pre-mission calibration including precise phase measurements made on ground. Such measurements are intended to match the phase of the chirp across PLO **20** switching interval. This calibration and measurements would increase pre-mission set up time and may become a drift term over time and temperature after calibration.

[0030] In the present invention, the phase continuous synthesizer includes a calibrator **90** to reduce the undesired phase discontinuities created during switching. Calibrating includes comparing the phase of the relatively wideband swept frequency signal output at the power divider **44** before and after successively switching between different frequency signals to determine the undesired phase discontinuities created during switching, and adjusting the phase of the offset frequency signal F_{off} generated by the offset DDS **140** to reduce the undesired phase discontinuities created during switching. The calibration includes a self-calibration feedback loop

defined by a phase locked loop (PLL) **92** receiving the reference frequency signal, a mixer **94** receiving the chirp or swept frequency signal output at the power divider **44** and a phase reference signal from the PLL **92**, an analog-to-digital (a/d) converter **96** receiving an output signal of the mixer, and the controller **100** which is connected to the a/d converter and provides a calibration signal to the offset DDS **140**. Referring to FIG. 3B, the phase discontinuity **B** created during switching is reduced or eliminated at time t_1 in the next chirp.

[0031] The PLL **92** is an auxiliary synthesizer added as a phase reference and is tuned to the frequency of the chirp at each switch point of the switch **80**. The phase of the chirp is compared with the PLL **92** before and after switching to determine the change in phase due to switching. In other words, the instantaneous phase difference between chirp and PLL **92** is measured before and after switching. Settling time is not a challenge because the PLL **92** is set to frequency well in advance of the calibration need. The result is correlated in the controller **100** against a mathematical chirp waveform and the error is returned as feedback to adjust the phase of the offset DDS **140**. Thus, the next chirp will reduce the phase difference during switching. The controller **100** determines the phase change needed, provides for averaging and resolves any $0^\circ/180^\circ$ ambiguity. Multiple settings may be provided in an adaptable lookup table to provide calibration at each switch point.

[0032] A plurality of approaches would be appropriate for determining the phase error. For example, a correlation method to maximize the cross-correlation between the desired and measured phase. Such a cross-correlation would

be calculated between ideal and measured or between mirror-image of pre-switched and post-switched waveforms. Another approach may be to calculate the standard deviation on the phase difference between before and after switching. Also, in yet another approach, the arcsine could be taken of mirrored pre-switch and non-mirrored post switch waveforms while linear and quadratic time is removed from the phase function. In these various approaches, linearization may be needed.

[0033] In sum, the fine tune DDS **10** produces a chirp but does not fully cover the required output sweep range. Switch **80** selects offset to put the chirp within the output sweep range. At switch points, DDS **10** is at highest frequency and is switched to lowest frequency as the coarse step is made with the switch **80**. The phase transient normally produced is adjusted out by changing the phase of the offset DDS **140** during the switching interval.

[0034] Previous embodiments utilized short duration RF switches to minimize the switching interval and reduce corresponding phase disturbances. However, such switches may not be readily available, and typically do not have good isolation from the switching signal to output. Phase continuity on either side of a switching transient is provided by phase calibration of the offset DDS **140**, but switching is not instantaneous. Break-before-make switches have reduced output during switching and transients caused by varying return loss. Make-before-break switches have increased output and reflection induced phase disturbances during switching. So the output of the synthesizer has continuous phase except during the switching interval where the transient distorts the phase.

[0035] Referring to FIGs. 4 and 5, another embodiment of the phase continuous synthesizer will be described. In the simplified diagram, the calibrator **90** of the previous embodiment is not illustrated but may certainly be included in the present embodiment. Here, a phase coasting unit **150** is connected downstream of the mixer **70** and band pass filter **42** to reduce the undesired phase discontinuities created during switching in the output frequency signal. In other words, the phase coasting unit will track the phase of the output frequency signal and coast over the region of phase/amplitude disturbance. The phase coasting unit **150** is preferably a high gain second or third-order phase locked loop (PLL) so there is little or no static phase error during frequency ramp. As an example of a third-order loop, the phase coasting unit **150** includes a phase detector **152**, a switch **154** connected to the phase detector and controlled to open during a switching interval, a plurality of integrators **156**, **158** downstream from the switch, and a voltage controlled oscillator **160** downstream from the plurality of integrators.

[0036] The analog switch **154** opens during the switching interval and holds the integrators **156**, **158** constant. The VCO **160** continues to ramp since the conditions are the same as if ramp were present during switching. Also, the controller **100** may pretune the phase coasting loop **150** to set initial conditions at the beginning of the chirp for fast acquisition. The output of the phase coasting unit **150** is a ramp of frequency due to the integrators **156**, **158** having fixed or zero voltage at their inputs. The blocks **151** and **153** schematically

illustrate the swept frequency signal before and after phase coasting respectively.

[0037] The phase continuous self-calibrating synthesizer and method of the present invention can increase the performance of SAR. The invention improves the ability to widen the chirp range and allows higher radiation tolerant technologies to be used without sweep range degradation. The present invention also allows the use of frequency division to reduce spurious frequencies rather than the conventional approach of multiplication. The coasting loop provides a near-ideal chirp that is continuous without transients. Also, the typical staircase frequency ramp from the DDS is smoothed out and appears as infinite granularity.

[0038] Other features of the phase continuous synthesizer may be described in greater detail in copending applications to the Assignee entitled "**PHASE-CONTINUOUS FREQUENCY SYNTHESIZER**" (attorney docket No. 51327) and "**SELF-CALIBRATING WIDEBAND PHASE CONTINUOUS SYNTHESIZER AND ASSOCIATED METHODS**" (attorney docket No. 51357), and filed concurrently herewith, the entire disclosures of each of which are incorporated by reference herein in their entirety.

[0039] Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and embodiments are intended to be included within the scope of the appended claims.